# CHAPTER 10

# HYDROSTATIC AND HYDRAULIC MACHINES

## CHAPTER LEARNING OBJECTIVES

*Upon completion of this chapter, you will be able to do the following:*

- *Explain the difference between hydrostatic and hydraulic liquids.*

- *Discuss the uses of hydrostatic machines.*

- *Discuss the uses of hydraulic machines.*

In this chapter we will discuss briefly the pressure of liquids: (1) hydrostatic (liquids at rest) and (2) hydraulic (liquids in motion). We will discuss the operation of hydrostatic and hydraulic machines and give applications for both types.

## HYDROSTATIC PRESSURE

You know that liquids exert pressure. The pressure exerted by seawater, or by any liquid at rest, is known as hydrostatic pressure.

If you are billeted on a submarine, you are more conscious of the hydrostatic pressure of seawater. When submerged, your submarine is squeezed from all sides by this pressure. A deep-sea diving submarine must be able to withstand the terrific force of water at great depths. Therefore, the air pressure within it must be equal to the hydrostatic pressure surrounding it.

### PRINCIPLES OF HYDROSTATIC PRESSURE

In chapter 9 you found out that all fluids exert pressure in all directions. That's simple enough. How great is the pressure? Try a little experiment. Place a pile of blocks in front of you on the table. Stick the tip of your finger under the first block from the top. Not much pressure on your finger, is there? Stick it between the third and fourth blocks. The pressure on your finger has increased. Now slide your finger under the bottom block in the pile. There you will find the pressure is greatest. The pressure increases as you go lower in the pile. You might say that pressure increases with depth. The same

is true in liquids. The deeper you go, the greater the pressure becomes. However, depth isn't the whole story.

Suppose the blocks in the preceding paragraph were made of lead. The pressure at any level in the pile would be considerably greater. Or suppose they were blocks of balsa wood-then the pressure at each level wouldn't be as great. Pressure, then, depends not only on the depth, but also on the weight of the material. Since you are dealing with pressure—force per unit of area, you will also be dealing with weight per unit of volume-or density.

When you talk about the density of a substance, you are talking about its weight per cubic foot or per cubic inch. For example, the density of water is 62.5 pounds per cubic foot; the density of lead is 710 pounds per cubic foot. However, to say that lead is heavier than water isn't a true statement. For instance, a 22-caliber bullet is the same density as a pail of water, but the pail of water is much heavier. It is true, however, that a cubic foot of lead is much heavier than a cubic foot of water.

Pressure depends on two principles-depth and density. You can easily find the pressure at any depth in any liquid by using the following formula:

$$P = H \times D$$

in which

$P$ = pressure, in lb per sq in. or lb per sq ft

$H$ = depth of the point, measured in feet or inches

and

$D$ = density in lb per cu in. or lb per cu ft

**Note:** If you use inches in your computation, you must use them throughout; if you use feet, you must use them throughout.

What is the pressure on 1 square foot of the surface of a submarine if the submarine is 200 feet below the surface? Using the formula:

$$P = H \times D$$

$$P = 200 \times 62.5 = 12{,}500 \text{ lb per sq ft}$$

Every square foot of the sub's surface that is at that depth has a force of more than 6 tons pushing in on it. If the height of the hull is 20 feet and the area in question is between the sub's top and bottom, you can see that the pressure on the hull will be at least $(200 - 10) \times 62.5 = 11{,}875$ pounds per square foot. The greatest pressure will be $(200 + 10) \times 62.5 = 13{,}125$ pounds per square foot. Obviously, the hull has to be very strong to withstand such pressures.

## USES OF HYDROSTATIC PRESSURE

Various shipboard operations depend on the use of hydrostatic pressure. For example, in handling depth charges, torpedoes, mines, and some types of aerial bombs, you'll be dealing with devices that operate by hydrostatic pressure. In addition, you'll deal with hydrostatic pressure in operations involving divers.

### Firing Depth Charges

Hiding below the surface exposes the submarine to great fluid pressure. However, it also gives the sub a great advantage because it is hard to hit and, therefore, hard to kill. A depth charge must explode within 30 to 50 feet of a submarine to cause damage. That means the depth charge must not go off until it has had time to sink to approximately the same level as the sub. Therefore, you use a firing mechanism that is set off by the pressure at the estimated depth of the submarine.

Figure 10-1 shows a depth charge and its interior components. A depth charge is a sheet-metal container filled with a high explosive and a firing device. A tube passes through its center from end to end. Fitted in one end of this tube is the booster, a load of granular TNT that sets off the main charge. It is also fitted with a safety fork and an inlet valve cover. Upon launching, the safety fork is knocked off, and the valve cover is removed to allow water to enter.

When the depth charge gets about 12 to 15 feet below the surface, the water pressure is sufficient to extend a bellows in the booster extender. The bellows
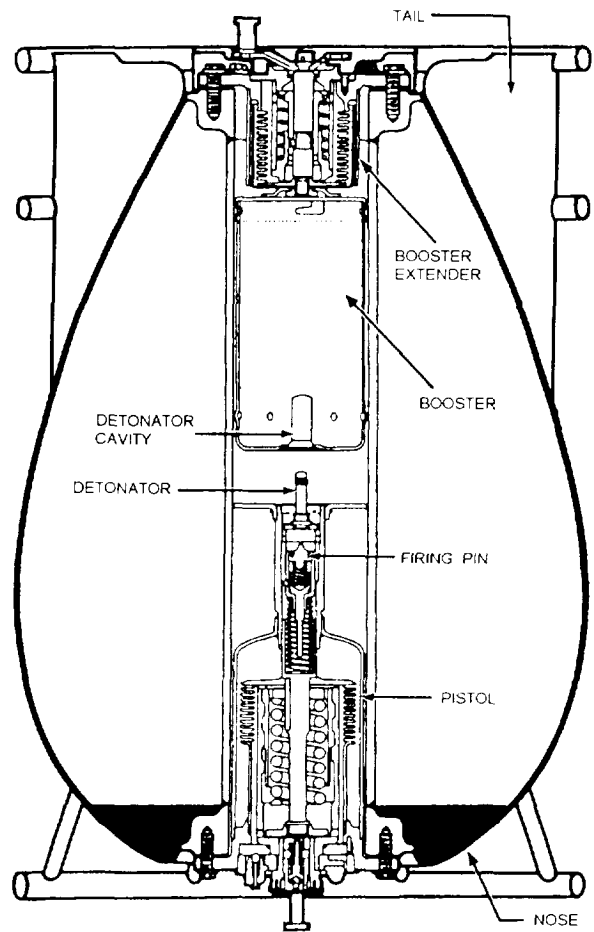


Figure 10-1.-A depth charge.

trips a release mechanism, and a spring pushes the booster up against the centering flange. Notice that the detonator fits into a pocket in the booster. Unless the detonator is in this pocket, it cannot set off the booster charge.

Nothing further happens until the detonator fires. As you can see, the detonator fits into the end of the pistol, with the firing pin aimed at the detonator base. The pistol also contains a bellows into which the water rushes as the charge goes down. As the pressure increases, the bellows begins to expand against the depth spring. You can adjust this spring so that the bellows will have to exert a predetermined force to compress it.

Figure 10-2 shows you the depth-setting dials of one type of depth charge. Since the pressure on the bellows depends directly on the depth, you can select any depth on the dial at which you wish the charge to go off. When the pressure in the bellows becomes sufficiently great, it releases the firing spring, which drives the firing pin
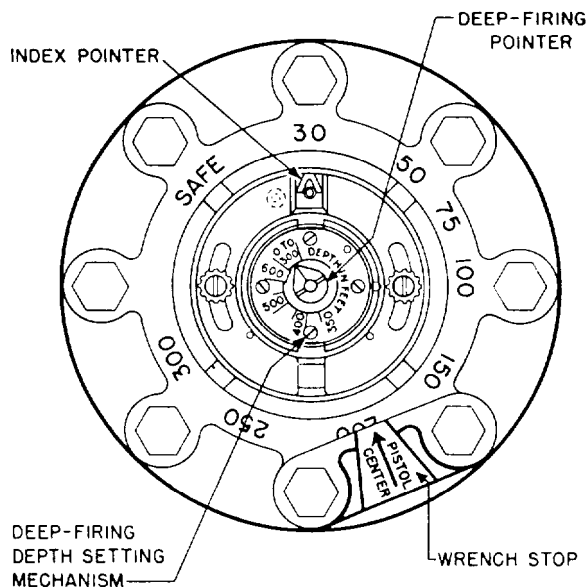
Figure 10-2.-Depth-setting dial.



Figure 10-3.-Inside a torpedo.

into the detonator. The booster, already in position, then fires and, in turn, sets off the entire load of TNT.

These two bellows—operated by hydrostatic pressure—serve two purposes. First, they permit the depth charge to fire at the proper depth; second, they make the charge safe to handle and carry. If you should accidentally knock the safety fork and the valve inlet cover off on deck, nothing would happen. Even if the detonator should go off while you were handling the charge, the main charge would not fire unless the booster was in the extended position.

## Guiding Torpedoes

To keep a torpedo on course toward its target is a job. Maintaining the proper compass course with a gyroscope is only part of the problem. The torpedo must travel at the proper depth so that it will neither pass under the target ship nor hop out of the water on the way.

As figure 10-3 shows, the torpedo contains an air-filled chamber sealed with a thin, flexible metal plate, or diaphragm. This diaphragm can bend upward or downward against the spring. You determine the spring tension by setting the depth-adjusting knob.

Suppose the torpedo starts to dive below the selected depth. The water, which enters the torpedo and surrounds the chamber, exerts an increased pressure on the diaphragm and causes it to bend down. If you follow the lever system, you can see that the pendulum will push forward. Notice that a valve rod connects the
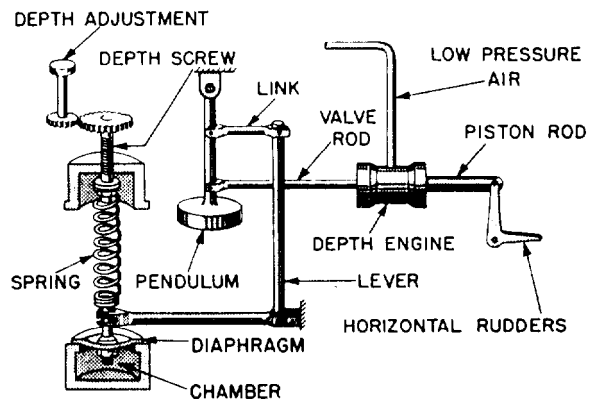
pendulum to the piston of the depth engine. As the piston moves to the left, low-pressure air from the torpedo's air supply enters the depth engine to the right of the piston and pushes it to the left. You must use a depth engine because the diaphragm is not strong enough to move the rudders.

The piston of the depth engine connects to the horizontal rudders as shown. When the piston moves to the left, the rudder turns upward and the torpedo begins to rise to the proper depth. If the nose goes up, the pendulum swings backward and keeps the rudder from elevating the torpedo too rapidly. As long as the torpedo runs at the selected depth, the pressure on the chamber remains constant and the rudders do not change from their horizontal position.

## Diving

Navy divers have a practical, first-hand knowledge of hydrostatic pressure. Think what happens to divers who go down 100 feet to work on a salvage job. The pressure on them at that depth is 8,524 pounds per square foot! Something must be done about that, or they would be flatter than a pancake.

To counterbalance this external pressure, a diver wears a rubber suit. A shipboard compressor then pumps pressurized air into the suit, which inflates it and provides oxygen to the diver's body as well. The oxygen enters the diver's lungs and bloodstream, which carries it to every part of the body. In that way the diver's internal pressure is equal to the hydrostatic pressure.

As the diver goes deeper, the air pressure increases to meet that of the water. In coming up, the pressure on the air is gradually reduced. If brought up too rapidly, the diver gets the "bends." That is, the air that was dissolved in the blood begins to come out of solution

10-3

and form bubbles in the veins. Any sudden release in the pressure on a fluid results in the freeing of some gases that are dissolved in the fluid. You have seen this happen when you suddenly relieve the pressure on a bottle of pop by removing the cap. The careful matching of hydrostatic pressure on the diver by air pressure in the diving suit is essential if diving is to be done at all.

**Determining Ship's Speed**

Did you ever wonder how the skipper knows the speed the ship is making through water? The skipper can get this information by using several instruments-the patent log, the engine revolution counter, and the pitometer (pit) log. The "pit log" operates, in part, by hydrostatic pressure. It really shows the difference between hydrostatic pressure and the pressure of the water flowing past the ship-but this difference can be used to find ship's speed.

Figure 10-4 shows a schematic drawing of a pitometer log. It consists of a double-wall tube that sticks out forward of the ship's hull into water that is not disturbed by the ship's motion. In the tip of the tube is an opening (A). When the ship is moving, two forces or pressures are acting on this opening: (1) the hydrostatic pressure caused by the depth of the water above the opening and (2) a pressure caused by the push of the ship through the water. The total pressure from these two forces transmits through the central tube (shown in white on the figure) to the left-hand arm of a manometer.

In the side of the tube is a second opening (B) that does not face the direction in which the ship is moving. Opening B passes through the outer wall of the double-wall tube, but not through the inner wall. The only pressure affecting opening B is the hydrostatic
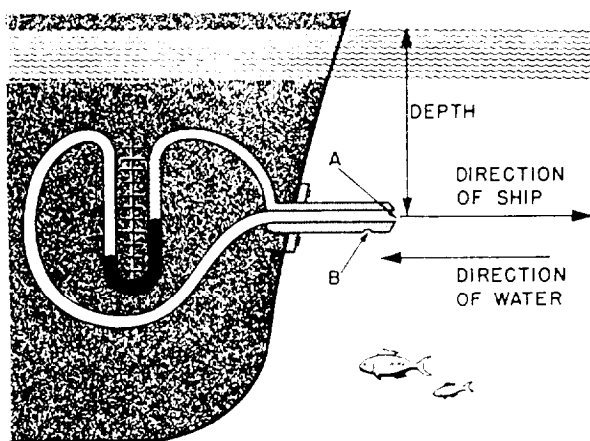


figure 10-4.-A pitometer log.

pressure. This pressure transmits through the outer tube (shaded in the drawing) to the right-hand arm of the manometer.

When the ship is dead in the water, the pressure through both openings A and B is the same, and the mercury in each arm of the manometer stands at the same level. However, as soon as the ship begins to move, additional pressure develops at opening A, and the mercury pushes down in the left-hand arm and up into the right-hand arm of the tube. The faster the ship goes, the greater this additional pressure becomes, and the greater the difference will be between the levels of the mercury in the two arms of the manometer. You can read the speed of the ship directly from the calibrated scale on the manometer.

Since air is also a fluid, the airspeed of an aircraft can be found by a similar device. You have probably seen the thin tube sticking out from the nose or the leading edge of a wing of the plane. Flyers call this tube a pitot tube. Its basic principle is the same as that of the pitometer log.

## HYDRAULIC PRESSURE

Perhaps your earliest contact with hydraulic pressure was when you got your first haircut. The hairdresser put a board across the arms of the chair, sat you on it, and began to pump the chair up to a convenient level. As you grew older, you probably discovered that the gas station attendant could put a car on the greasing rack and-by some mysterious arrangement-jack it head high. The attendant may have told you that oil under pressure below the piston was doing the job.

Come to think about it, you've probably known something about hydraulics for a long time. Automobiles and airplanes use hydraulic brakes. As a sailor, you'll have to operate many hydraulic machines. You'll want to understand the basic principles on which they work.

Primitive man used simple machines such as the lever, the inclined plane, the pulley, the wedge, and the wheel and axle. It was considerably later before someone discovered that you could use liquids and gases to exert forces at a distance. Then, a vast number of new machines appeared. A machine that transmits forces by a liquid is a hydraulic machine. A variation of the hydraulic machine is the type that operates with a compressed gas. This type is known as the pneumatic machine. This chapter deals only with basic hydraulic machines.
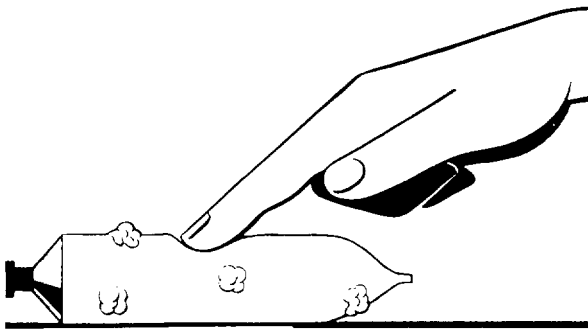
Figure 10-5.-Pressure to a fluid transmits in all directions.



Figure 10-6.-Hydraulic brakes.

## PRINCIPLES OF HYDRAULIC PRESSURE

A Frenchman named Pascal discovered that a pressure applied to any part of a confined fluid transmits to every other part with no loss. The pressure acts with equal force on all equal areas of the confining walls and perpendicular to the walls.

Remember when you are talking about the hydraulic machine, you are talking about the way a liquid acts in a closed system of pipes and cylinders. The action of a liquid under such conditions is somewhat different from its behavior in open containers or in lakes, rivers, or oceans. You also should keep in mind that you cannot compress most liquids into a smaller space. Liquids don't "give" the way air does when you apply pressure, nor do liquids expand when you remove pressure.

Punch a hole in a tube of toothpaste. If you push down at any point on the tube, the toothpaste comes out of the hole. Your force has transmitted from one place to another through the toothpaste, which is a thick, liquid fluid. Figure 10-5 shows what would happen if you punched four holes in the tube. If you were to press on the tube at one point, the toothpaste would come out of all four holes. You have illustrated a basic principle of hydraulic machines. That is, a force applied on a liquid transmits equally in every direction to all parts of the container.

We use this principle in the operation of four-wheel hydraulic automobile brakes. Figure 10-6 is a simplified drawing of this brake system. You push down on the brake pedal and force the piston in the master cylinder against the fluid in that cylinder. This push sets up a pressure on the fluid as your finger did on the toothpaste in the tube. The pressure on the fluid in the master cylinder transmits through the lines to the brake cylinders in each wheel. This fluid under pressure
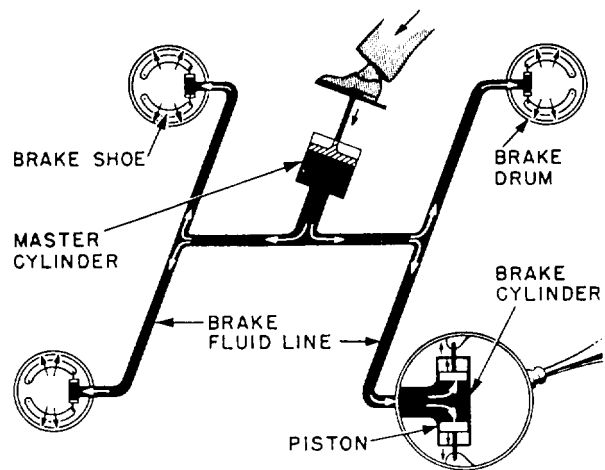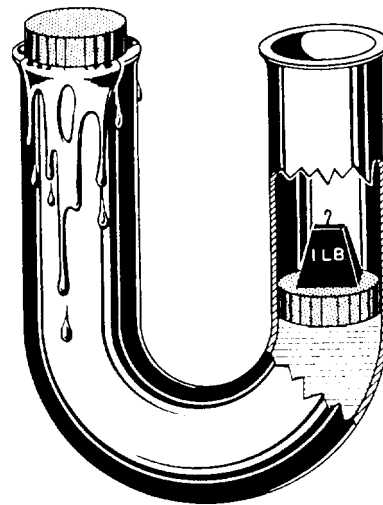


Figure 10-7.-Liquid transmits force.

pushes against the pistons in each of the brake cylinders and forces the brake shoes out against the drums.

## MECHANICAL ADVANTAGES OF HYDRAULIC PRESSURE

Another aspect to understand about hydraulic machines is the relationship between the force you apply and the result you get. Figure 10-7 will help you understand this principle. The U-shaped tube has a cross-sectional area of 1 square inch. In each arm is a piston that fits snugly, but can move up and down. If you place a 1-pound weight on one piston, the other one will push out the top of its arm immediately. If you place a
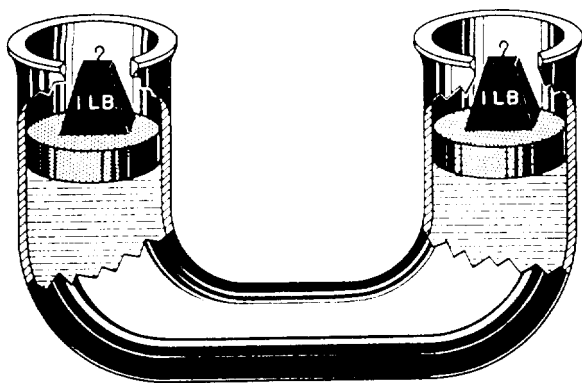
Figure 10-8.-Equal pressure applied at each end of a tube containing a liquid.
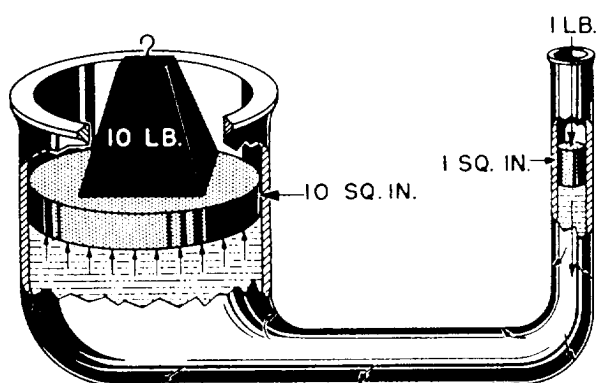


Figure 10-9.-A mechanical advantage of 10.

1-pound weight on each piston, however, each one will remain in its original position, as shown in figure 10-8.

Thus, you see that a pressure of 1 pound per square inch applied downward on the right-hand piston exerts a pressure of 1 pound per square inch upward against the left-hand one. Not only does the force transmit through the liquid around the curve, it transmits equally on each unit area of the container. It makes no difference how long the connecting tube is or how many turns it makes. It is important that the entire system be full of liquid. Hydraulic systems will fail to operate properly if air is present in the lines or cylinders.

Now look at figure 10-9. The piston on the right has an area of 1 square inch, but the piston on the left has an area of 10 square inches. If you push down on the smaller piston with a force of 1 pound, the liquid will transmit this pressure to every square inch of surface in the system. Since the left-hand piston has an area of 10 square inches, each square inch has a force of 1 pound

transmitted to it. The total effect is a push on the larger piston with a total force of 10 pounds. Set a 10-pound weight on the larger piston and it will support the 1-pound force of the smaller piston. You then have a 1-pound push resulting in a 10-pound force. That's a mechanical advantage of 10. This mechanical advantage is why hydraulic machines are important.

Here's a formula that will help you to figure the forces that act in a hydraulic machine:

$$\frac{F_1}{F_2} = \frac{A_1}{A_2}$$

In that,

$F_1$ = force, in pounds, applied to the small piston;

$F_2$ = force, in pounds, applied to the large piston;

$A_1$ = area of the small piston, in square inches; and

$A_2$ = area of the large piston, in square inches.

Let's apply the formula to the hydraulic press shown in figure 10-10. The large piston has an area of 90 square inches, and the smaller one has an area of 2 square inches. The handle exerts a total force of 15 pounds on the small piston. With what total force could you raise the large piston?

Write down the formula

$$\frac{F_1}{F_1} = \frac{A_1}{A_2}.$$

Substitute the known values

$$\frac{15}{F_2} = \frac{2}{90}$$

and

$$F_2 = \frac{90 \times 15}{2} = 675 \text{ pounds.}$$

## USES OF HYDRAULIC PRESSURE

You know from your experience with levers that you can't get something for nothing. Applying this knowledge to the simple system in figure 10-9, you know that you can't get a 10-pound force from a
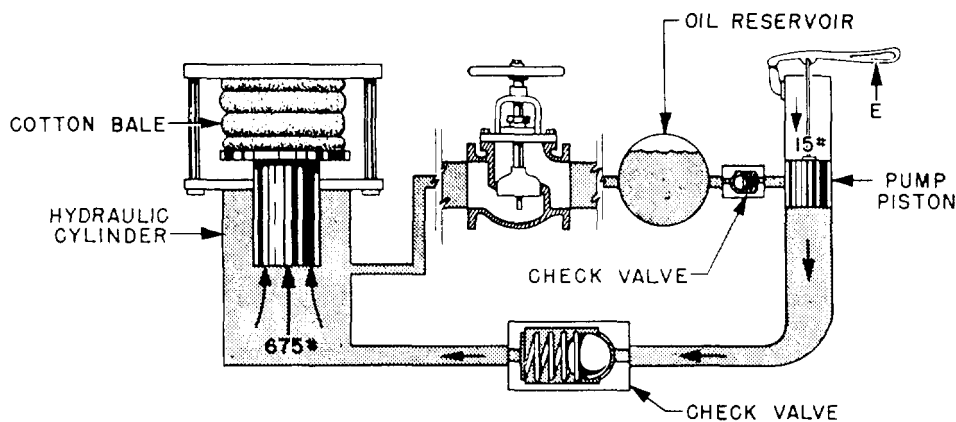
Figure 10-10.-Hydraulic press.

1-pound effort without sacrificing distance. You must apply the 1-pound effort through a much greater distance than the 10-pound force will move. To raise the 10-pound weight a distance of 1 foot, you must apply the 1-pound effort through what distance? Remember, if you neglect friction, the work done on any machine equals the work done by that machine. Use the work formula to find how far the smaller piston will have to move.

Work input = Work output

$$F_1 \times D_1 = F_2 \times D_2$$

By substituting

$$1 \times D_1 = 10 \times 1$$

you find that

$$D_1 = 10 \text{ feet}$$

The smaller piston will have to move a distance of 10 feet to raise the 10-pound load 1 foot. It looks then as though the smaller cylinder would have to be at least 10 feet long—and that wouldn't be practical. In addition, it isn't necessary if you put a valve in the system.

The hydraulic press in figure 10-10 contains a valve. As the small piston moves down, it forces the fluid past check valve A into the large cylinder. As soon as the small piston moves upward, it removes the pressure to the right of check valve A. The pressure of the fluid on the check valve spring below the large piston helps force

that valve shut. The liquid that has passed through the valve opening on the down stroke of the small piston is trapped in the large cylinder.

The small piston rises on the upstroke until its bottom passes the opening to the fluid reservoir. More fluid is sucked past check valve B and into the small cylinder. The next downstroke forces this new charge of fluid out of the small cylinder past the check valve into the large cylinder. This process repeats stroke by stroke until enough fluid has been forced into the large cylinder to raise the large piston the required distance of 1 foot. The force has been applied through a distance of 10 feet on the pump handle. However, it was done through a series of relatively short strokes, the total of the strokes being equal to 10 feet.

Maybe you're beginning to wonder how the large piston gets back down after the process is finished. The fluid can't run back past check valve B-that's obvious, Therefore, you lower the piston by letting the oil flow back into the reservoir through a return line. Notice that a simple globe valve is in this line. When the globe valve opens, the fluid flows back into the reservoir. Of course, this valve is shut while the pump is in operation.

### Aiding the Helmsman

You've probably seen the helmsman swing a ship weighing thousands of tons almost as easily as you turn your car. No, helmsmen are not superhuman. They control the ship with machines. Many of these machines are hydraulic.

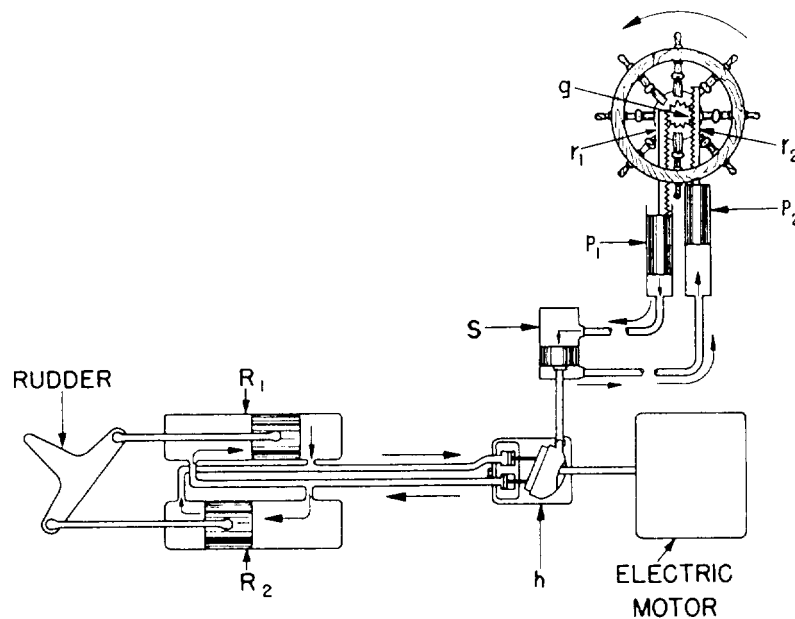There are several types of hydraulic and electro-hydraulic steering mechanisms. The simplified diagram

**Figure 10-11.-Electrohydraulic steering mechanism.**

in figure 10-11 will help you to understand the general principles of their operation. As the hand steering wheel turns in a counterclockwise direction, its motion turns the pinion gear (g). This causes the left-hand rack ($r_1$) to move downward and the right-hand rack ($r_2$) to move upward. Notice that each rack attaches to a piston ($p_1$ or $p_2$). The downward motion of rack $r_1$ moves piston $p_1$ downward in its cylinder and pushes the oil out of that cylinder through the line. At the same time, piston $p_2$ moves upward and pulls oil from the right-hand line into the right-hand cylinder.

If you follow these two lines, you see that they enter a hydraulic cylinder (S). One line enters above and one below the single piston in that cylinder. This piston and the attached plunger are pushed down toward the hydraulic pump (h) in the direction of the oil flow shown in the diagram. So far in this operation, hand power has been used to develop enough oil pressure to move the control plunger attached to the hydraulic pump. At this point, an electric motor takes over and drives the pump (h).

Oil is pumped under pressure to the two big steering rams ($R_1$ and $R_2$). You can see that the pistons in these rams connect directly to the rudder crosshead that controls the position of the rudder. With the pump operating in the direction shown, the ship's rudder is thrown to the left, and the bow will swing to port. This operation shows how a small force applied on the steering wheel sets in motion a series of operations that result in a force of thousands of pounds.

**Getting Planes on Deck**

The swift, smooth power required to get airplanes from the hanger deck to the flight deck of a carrier is provided by a hydraulic lift. Figure 10-12 shows how this lifting is done. An electric motor drives a variable-speed gear pump. Oil enters the pump from the reservoir and is forced through the lines to four hydraulic rams. The pistons of the rams raise the elevator platform. The oil under pressure exerts its force on each square inch of surface area of the four pistons. Since the pistons are large, a large total lifting force results. Either reversing the pump or opening valve 1 and closing valve 2 lowers the elevator. The weight of the elevator then forces the oil out of the cylinders and back into the reservoir.

**Operating Submarines**

Another application of hydraulics is the operation of submarines. Inside a submarine, between the outer skin and the pressure hull, are several tanks of various design and purpose. These tanks control the total weight of the ship, allowing it to submerge or surface. They also control the trim or balance, fore and aft, of the submarine. The main ballast tanks have the primary function of either destroying or restoring positive buoyancy to the submarine. Allowing air to escape through hydraulically operated vents at the top of the tanks lets seawater enter through the flood ports at the bottom to replace the air. For the sub to regain positive buoyancy, the tanks are "blown" free of seawater with
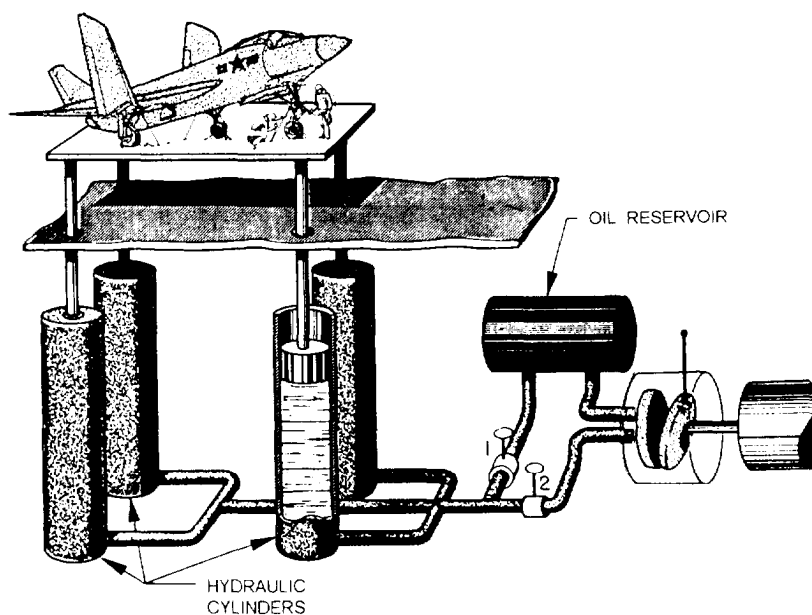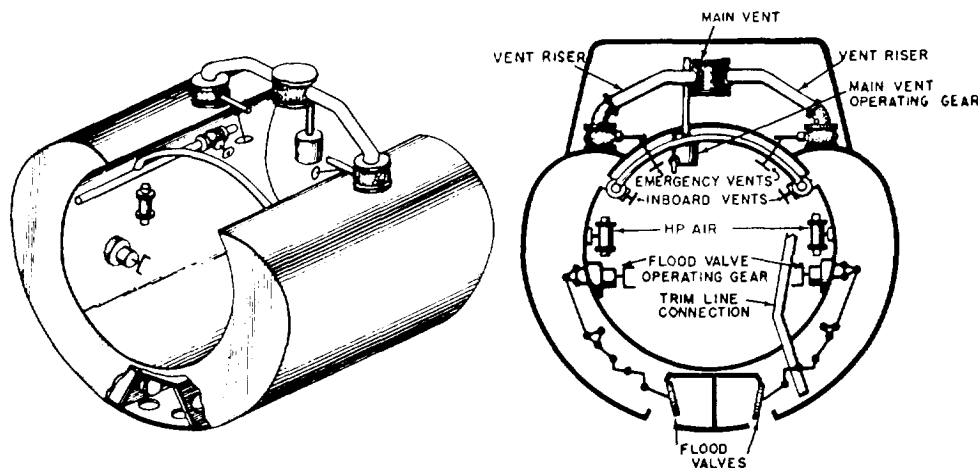
**Figure 10-12.-Hydraulic lift.**



**Figure 10-13.-Submarine special ballast tank (safety tank).**

compressed air. Sufficient air is left trapped in the tanks to prevent the seawater from reentering.

We use other tanks, such as variable ballast tanks and special ballast tanks (for example, the negative tank, safety tank, and bow buoyancy tank), either for controlling trim or stability or for emergency weight-compensating purposes. The variable ballast tanks have no direct connection to the sea. Therefore, we must pump water into or out of them. The negative tank and the safety tank can open to the sea through large flood valves. These valves, as well as the vent valves for the main ballast tanks and those for the safety and negative tanks, are all hydraulically operated.

The vents and flood valves are outside the pressure hull, so some means of remote control is needed to open and close them from within the submarine. We use hydraulic pumps, lines, and rams for this purpose. Oil pumped through tubing running through the pressure hull actuates the valve's operating mechanisms by exerting pressure on and moving a piston in a hydraulic cylinder. Operating the valves by a hydraulic system from a control room is easier and simpler than doing so by a mechanical system of gears, shafts, and levers. The hydraulic lines can be readily led around corners and obstructions, and a minimum of moving parts is required.

Figure 10-13 is a schematic sketch of the safety tank-one of the special ballast tanks in a submarine. The main vent and the flood valves of this tank operate
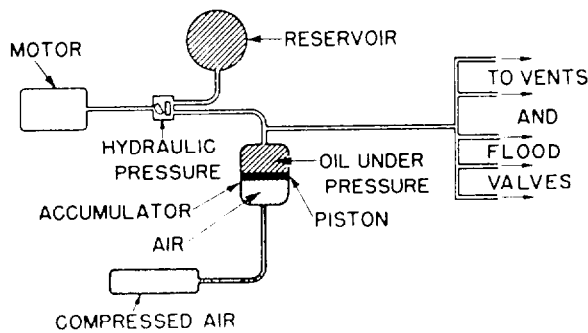
**Figure 10-14.-Controlling fluid pressure.**

hydraulically by remote control, although in an emergency they may operate manually.

Hydraulics are used in many other ways aboard submarines. They are used to raise and lower the periscope. The submarines are steered and the bow and stern planes are controlled by hydraulic systems. The windlass and capstan system, used in mooring the submarine, is hydraulically operated. You will find many more applications of hydraulics aboard the submarine.

**Controlling Fluid Pressure**

In some hydraulic systems, oil is kept under pressure in a container known as an accumulator. As shown in figure 11-14, the accumulator is a large cylinder; oil is pumped into it from the top. A free piston divides the cylinder into two parts. Compressed air is forced into the cylinder below the piston at a pressure of 600 psi. Oil is then forced into it on top of the piston. As the pressure above it increases, the piston is forced down, squeezing the air into a smaller space. Air is elastic; you can compress it under pressure, and it will expand as soon as the pressure is reduced. When oil pressure is reduced, large quantities of oil under working pressure are instantly available to operate hydraulic rams or motors any place on the submarine.

## SUMMARY

The Navy uses many devices whose operation depends on the hydrostatic principle. You should remember three points about the operation of these devices:

Pressure in a liquid is exerted equally in all directions.

Hydrostatic pressure refers to pressure at any depth in a liquid that is not flowing.

Pressure depends upon both depth and density.

The formula for finding pressure is

$P = H \times D$

The working principle of all hydraulic mechanisms is simple enough. Whenever you find an application that seems hard to understand, keep these points in mind:

*Hydraulics* is the term applied to the behavior of enclosed liquids. Machines that operate liquids under pressure are called hydraulic machines.

Liquids are incompressible. They cannot be squeezed into spaces smaller than they originally occupied.

A force applied on any area of a confined liquid transmits equally to every part of that liquid.

In hydraulic cylinders, the relation between the force exerted by the large piston to the force applied on the smaller piston is the same as the relationship between the area of the larger piston and the area of the smaller piston.

Some of the advantages of hydraulic machines are:

We use tubing to transmit forces, and tubing can readily transmit forces around corners.

Tubing requires little space.

Few moving parts are required.